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PHOTONIC CRYSTAL FIBER BASED ENTANGLED PHOTON SOURCES

MICHIGAN TECHNOLOGICAL UNIVERSITY

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14. ABSTRACT
We generate high-purity correlated and entangled photon-pairs at the telecom wavelengths in a cooled 10-meter highly nonlinear fiber (HNLF). In our previous project (contract no: FA8750-12-1-0136), we were able to generate correlated/entangled photon-pair using the highly nonlinear fiber in a counter-propagating scheme (CPS). With the HNLF at room temperature, we obtain coincidence-to-accidental ratio (CAR) ~ 26-30 and two-photon interference with visibility ~ 92%-93%. This is the best performance compared to the reported results in the literature on HNLF and Photonic Crystal Fiber (PCF) at telecom wavelengths. Unlike the PCF or microstructure fiber, the HNLF can be cooled at liquid nitrogen temperatures (77K) to suppress Raman photons. By cooling the HNLF, we expect to obtain a CAR ~130 and two-photon interference with visibility > 98%. We will verify the non-local behavior of high-purity HNLF-based entangled photon-pairs by making Bell's Inequalities measurements. We investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of polarization-entangled photon-pairs is better preserved than polarization-correlated photon-pairs in multiple scattering processes.

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Abstract

We generate high-purity of correlated and entangled photon-pairs at the telecom wavelengths in a cooled 10-meter highly nonlinear fiber (HNLF). The HNLF is a solid fiber and Ge-doped with the nonlinear coupling coefficient of γ = 30/W-km. We are able to generate correlated/entangled photon-pairs using the highly nonlinear fiber in a counter-propagating scheme (CPS). With the HNLF at room temperature, we obtain a coincidence to accidental ratio (CAR) ~ 26-30 and two-photon interference with visibility ~ 92%-93%. This is the best performance compared to the reported results in the literature on HNLF and Photonic Crystal Fiber (PCF) at telecom wavelengths. Unlike the PCF or microstructure fiber, the HNLF can be cooled at liquid nitrogen temperature (77K) to suppress Raman photons. By cooling the HNLF, we expect to obtain a CAR ~130 and two-photon interference with visibility > 98%. We will verify the non-local behavior of high-purity HNLF-based entangled photon-pairs by making Bell's Inequalities measurements. We investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of polarization-entangled photon-pairs is better preserved than polarization-correlated photon-pairs in multiple scattering processes.

1 SUMMARY

The entangled photon-pair is a fundamentally quantum state of light which can provide exciting potential applications in quantum key generation. In order to implement entanglement based quantum key generation, there needs to be a practical source of entangled photon-pairs. Up to now, laboratory experiments have been used to produce entangled light and all have had some practical issues. Using fiber is advantageous because it can be easily interfaced with low loss to the most common transmission medium, namely fiber optical cable. The fiber based entanglement sources have excellent modal purity, high spectral brightness, large bandwidth, potentially broad tunability, and convenient packaging options. In this project, we built a counter propagating scheme for generating polarization entangled photon pairs at telecom wavelengths. We use 10 m of highly nonlinear fiber. We measure a coincidence to accidental ratio to verify the purity of photon-pairs. With the HNLF at room temperature, we obtain a coincidence to accidental ratio (CAR) ~ 26-30 and two-photon interference with visibility ~ 92%-93%. This is the best performance compared to the reported results in the literature on HNLF and Photonic Crystal Fiber (PCF) at telecom wavelengths. Unlike the PCF or microstructure fiber, the HNLF can be cooled at liquid nitrogen temperature (77K) to suppress Raman photons. By cooling the HNLF, we expect to obtain a CAR ~130 and two-photon interference with visibility > 98%. We will verify the non-local behavior of high-purity HNLF based entangled photon-pairs by making Bell's Inequalities measurements. We investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of polarization-entangled photon-pairs is better preserved than polarization-correlated photon-pairs in multiple scattering processes.

2 INTRODUCTION

Entanglement and superposition are foundations for the emerging field of quantum communication and information processing. These two fundamental features of quantum mechanics have made (i) the potential for quantum computation faster than any known classical computation and (ii) quantum key distribution unconditionally secure compared to communication based on classical key distribution. The main challenge of developing a new entanglement source is to make sure the source can provide an efficient and scalable quantum information processor. They are usually generated through nonlinear interaction processes in $\chi(2)$ [1] and $\chi(3)$ [2] media.

Entanglement distribution over long distances is an important experimental challenge in quantum information processing because of unavoidable transmission loss associated with low coupling efficiency from free space to optical fibers. There are a few experimental approaches to resolve transmission loss by using coherent light sources. In quantum cryptography, weak coherent pulses have been used as a substitute for single photon sources in implementing BB84, where the polarization state of the coherent light pulse is encoded as a qubit for information processing [3,4]. Yuen's keyed communication (KCQ) approach [5,6,7] has made use of inherent quantum noise of coherent states to perform the cryptographic function of data encryption. The advantage of using a coherent state compared to a single photon state and squeezed state is that it can easily be generated and detected.

Entangled photons have very unusual properties stemming from their unique quantum mechanical nature. Such properties have allowed entangled photons to enable a number of important scientific experiments including the violation of Bell's inequality, thereby demonstrating a counterintuitive but fundamentally quantum mechanical 'action-at-a-distance' between two physically separated but entangled states, the first demonstration of quantum teleportation, and entanglement swapping [8-10]. We developed a source of entangled photons based on nonlinear interactions in a highly nonlinear fiber. Such sources have various benefits, for instance inherent compatibility with standard fiber optics and a high modal quality that allows repeated quantum operations.

We make use of $\chi(3)$ –non-linearity of highly nonlinear fiber to generate correlated/entangled photon-pairs through the four-wave mixing process. Two pump photons (ω_p) are annihilated in creating the energy-time correlated signal (ω_s) and idler (ω_i) photons. This process conserves energy and momentum such that $2\omega_p = \omega_s + \omega_i$ and $2k_p = k_s + ki$,

respectively. In addition to the four-wave mixing process, Raman photons at the signal and idler wavelengths can also be generated in the fiber.

Raman photons are produced when pump photons couple with inhomogeneously-broadened vibrational Raman modes of the silica molecules [11,12]. The best mitigation strategy is to reduce the strength of vibrational Raman modes by cooling the fiber i.e. to suppress the Raman scattering process. However, not all the fiber based entangled photon sources can be cooled such as photonic crystal fiber. A dispersion shifted-fiber (DSF) and a highly nonlinear fiber (HNLF) can be cooled at the liquid nitrogen temperature (77K). The advantage of the HNLF is a larger nonlinear coupling coefficient of γ = 30 (W·km)-1 (our HNLF is provided by SUMITOMO) compared to the dispersion shifted-fiber (DSF) of γ = 2 (W·km)-1.

In this final report, we describe the generated high-purity correlated/entangled photon-pairs in a 10 m highly nonlinear fiber at the liquid nitrogen temperature (77K). With the cooled HNLF, we obtain the high purity of correlated photon pair with coincidence to accidental ratio (CAR) ~ 130. The high-purity correlated photon pairs are then used to generate a two-photon polarization entangled state |Hi Hs⟩ + |Vi Vs⟩ through a counter-propagating scheme (CPS). We measure the two-photon interference of the entangled photon pair. We obtain the visibility of two-photon interference greater than 98%, which is the desired benchmark for all quantum key generation protocols [13].

We have achieved the following objectives of the project:

(1) As for the perfect correlated and entangled photon-pair source, we have developed a short highly nonlinear fiber~10 meters to replace a 300 meters of dispersion shifted-fiber which helps to integrate the source into a small platform.

(2) We have obtained two-photon interference (TPI) with a visibility of ~92% with the HNLF at room temperature. In this work, we cool the HNLF at liquid nitrogen temperature (77K), and obtain the two-photon interference with visibility > 98% [13].

(3) We investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of the polarization-entangled photon-pair is better preserved than a polarization-correlated photon-pair in multiple scattering processes [14,15].

3 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Problem Description

Practical fiber based entangled photon sources are needed to enable quantum communication systems. One of the main difficulties of fiber-based entanglement is spontaneous Raman scattering. Raman photons at the same wavelength as the signal and idler photons add noise and reduce the fidelity of correlation and entanglement of the photon-pairs. The fiber can be cooled to liquid nitrogen temperature at 77K so as to reduce the spontaneous Raman scattering process. Two-photon interference with visibility of 98% has been achieved by cooling the fiber [2]. However, not all the fiber based entangled photon sources, such as photonic crystal fibers (PCF), can be cooled.

The air hole photonic crystal fiber (PCF) or microstructure fiber has the nonlinear coupling coefficient $\sim$ 70 $(W \cdot km)^{-1}$. However, the air hole PCF has low quality photon-pairs at telecom wavelengths because of the complexity of polarization mode, low coupling efficiency, and Raman photons. The best visibility of two-photon interference (TPI) obtainable from the air hole PCF is around 80% [16,17]. Unlike highly nonlinear fiber (HNLF), we cannot cool the PCF to liquid nitrogen temperatures (77K) so the Raman photons cannot be suppressed.

In this project, we used a highly nonlinear fiber as an entanglement source for generating high quality photon-pairs in a counter-propagating scheme. We specify a design for the counter-propagating scheme (CPS) with short, highly nonlinear fiber, which has the advantage of being extremely easy-to-use, thus opening the door for non-experts to use entangled photon-pairs.

3.2 Research Objectives

The first task of this project is to characterize the purity of the photon-pairs generated in the HNLF, which is cooled at liquid nitrogen temperature (77K). We measure coincidence to accidental ratio (CAR) for verifying the purity of photon-pair. Then, we use a counter-propagating scheme for generating two-photon polarization entangled photon-pairs in the cooled fiber. We then measure the two-photon interference (TPI) of the entangled photon-pairs. We justify the non-local behavior of the entangled photon-pairs by making Bell's inequalities measurements.

Second, we investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of polarization-entangled photon-pairs is better preserved than polarization-correlated photon-pairs in the multiple scattering

processes. We also investigate the effect of standard loss and multiple scattering on fiber based photon-pairs. We observe that the existence of Raman photons in a fiber based photon-pair source can enhance depolarization effect in random media.

3.3 Technical Approach

3.3.1 Correlated Photon-Pair: Coincidence to Accidental Ratio (CAR)

Cooling the HNLF: We will use 10 meters of highly nonlinear fiber (HNLF) provided by SUMIMOTO. The HNLF is a solid fiber and Ge-doped. We cool the HNLF in a small dewar as shown in Fig.1. The loss due to fiber bending and handling, even in this low temperature environment is negligible. The loss due to cooling the fiber is less than 4% at 77K. Cooling the fiber also causes contraction of the fiber length, which in turn shortens the propagation time for the photon-pairs to arrive at the detectors. The advancement of the arrival time is around 160 ps at temperature of 77K.

It is known that Stokes and anti-Stokes Raman-scattering noise photons are emitted at a rate proportional to n_{th} + 1 and n_{th}, respectively, where n_{th} = 1 / [exp ($h\nu$ / $k_B T$) - 1] is the Bose population factor, ν is the frequency shift of Stokes and anti-Stokes from the pump frequency, T is the temperature of the fiber, h is Planck's constant, and k_B is Boltzmann's constant.

Fig.1. Showing the 10 m of HNLF and a dewar for cooling the fiber.

Raman Photon Reduced Factor: In our experiment, the signal and idler photons are selected with their wavelengths detuning about 5 nm away from the pump wavelength. When we cool the HNLF, the Bose factor for the Stokes and anti-Stokes photons are reduced as illustrated in Table 1.

Table I: Stokes, Anti-Stokes Raman photon, CAR and TPI with the Cooled HNLF

Temperature	300 K (room)	77 K (LN$_2$)
Bose factor -Stokes	10.8	3.16
Bose factor - Anti-Stokes	9.8	2.16
Raman Photon Reduced Factor		Stokes = 10.8/3.6 = 3.0 Anti-Stokes= 9.8/2.16=4.5
CAR	~30:1	30:1/4 $\rightarrow$ 120: 1
TPI visibility	> 92%	> 98%

At room temperature (300 K), we calculate the Bose factors for Stokes and anti-Stokes about 10.8 and 9.8, respectively. At 77 K, the Bose factors for Stokes and anti-Stokes are reduced by 3.16 and 2.16 respectively. This means that we can suppress the Raman scattering process by cooling the fiber. From here, we estimate the Raman photon reduced factor (RF) for Stokes (S) and anti-Stokes (AS) at 77 K compared to their parameters at 300K as $S_{RF}(77K)$ = 10.8/3.6 = 3.0 and AS(77 K) = 9.8/2.16 = 4.5, respectively. Then, the average Raman photon reduced factor at 77K for the Stokes and anti-Stokes is about 4.

CPS with Cooled Fiber: We use the counter-propagating scheme (CPS) to generate
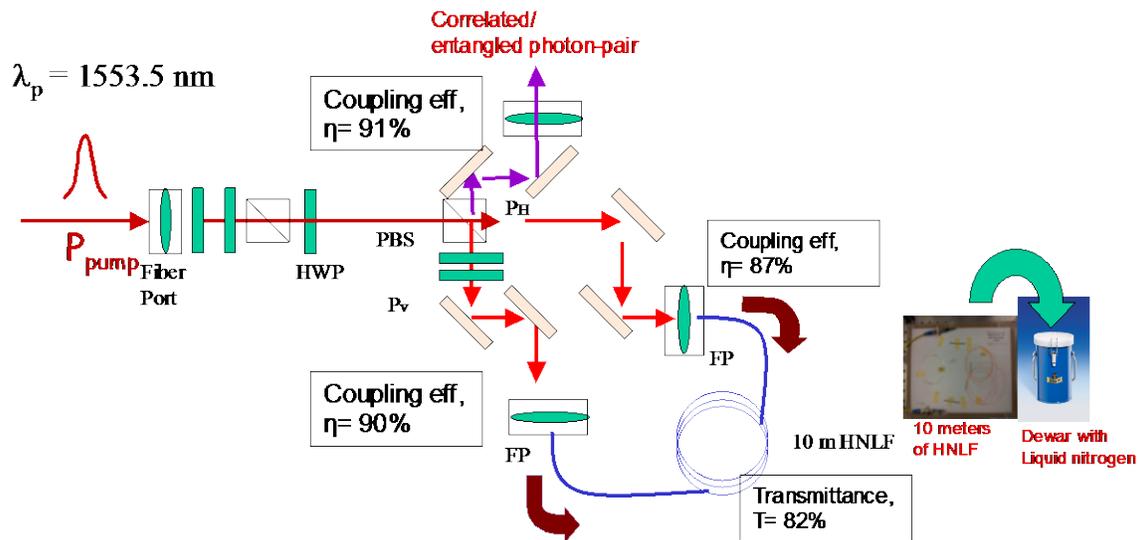
Fig. 2. The diagram of the counter-propagating scheme. FP: fiber port (free-space to fiber). PBS: polarization beam splitter. LP: Linear Polarizer.

entangled photon-pairs in the cooled 10 m HNLF. The schematic diagram of the counter-propagating scheme (CPS) is shown in Fig. 2. Briefly, a single 45°-polarized pump pulse is split into two equally powered, orthogonally polarized components P_H and P_V in the polarization beam-splitter (PBS). The clockwise and counter-clockwise pump pulses create signal/idler photon-pairs with probability amplitudes $|H_iH_s\rangle$ and $|V_iV_s\rangle$, respectively. After propagating through the fiber, these two amplitudes are then coherently superimposed through the same PBS. This common-path polarization interferometer has good stability to keep zero relative phase between horizontally and vertically polarized pumps and is capable of creating polarization entanglement $|H_i H_s\rangle + |V_i V_s\rangle$ at the output of the PBS.

4   FINAL RESULTS AND ACCOMPLISHMENT

Below is the summary of our findings.

1).With the cooled HNLF at 77K, we obtain a CAR of 130 ±5, two-photon interference with visibility 〉98%, and the violation of Bell's inequality, |S|=2.788 $\pm$ 0.064 (> 12σ) [13].

2). Standard loss and multiple scattering processes in the transmission channel is detrimental to the quantum correlation of both polarization-correlated and polarization-entangled photon-pairs. The deterioration of the photon-pair's correlation is inversely proportional to the scattering mean free path.

3). Polarization entanglement of photon-pairs is better preserved as it propagates through multiple scattering random media [14].

4). Raman noise photons increase the depolarization/decoherence effect on the two photon state [15].

4.1   The Overall Project Accomplishment

The project accomplishments fall into two main categories: (a) quality of correlated/entangled photon-pairs generated in a cooled 10 m length of HNLF at 77K and (b) its application through a random medium as for exploring multiple scattering effects on the photon-pair.

(a). Quality of HNLF based correlated/entangled photon-pairs.

In this project, we use a 10 m length of HNLF at 77K for generating polarization correlated/entangled photon pairs at the telecom wavelengths in a counter propagating scheme. Then, we use the photon-pair to generate two-photon polarization entangled state $|H_i\ H_s\rangle + |\ V_i\ V_s\rangle$ and obtain two-photon interference with visibility about 98%. We also verify the non-local behavior of the entangled photon-pairs by making the Bell's inequality measurements.

(b). A Correlated/Entangled Photon Pair through a random media.

In this work, we demonstrate an experimental study on the effect of multiple scattering on quantum correlation of telecom wavelength photon-pairs. We demonstrate that multiple scattering in the transmission channel is detrimental to the quantum correlation of both polarization-correlated and polarization-entangled photon-pairs. In addition, we observe that the polarization-entangled photon-pair is better preserved as it propagates through multiple scattering random media; hence will be a superior candidate for free space long distance quantum key distribution compared to correlated photon-pair.

4.2   A cooled 10m Highly Nonlinear fiber based Photon-Pair Source

The coincidences and accidental correlations for the photon-pairs generated in a cooled 10m length of HNLF are measured and shown in Fig.3. Then, we use the data to plot the coincidences to accidental ratio (CAR) as shown in Fig.4. The CAR measurement is performed on the HNLF at 77K. The HNLF in plastic buffer coating is cooled to 77K by immersing it into a liquid nitrogen filled Dewar. Advancement of photons arrival times by about 160 ps indicates contraction in fiber length when the HNLF is cooled to 77K. It is also noted that the zero dispersion wavelength of the HNLF is shifted toward shorter wavelengths at 77K. Fig. 4 shows the measurement of CAR for different pump powers at 77K. An optimum CAR value of about 130 is obtained at 77K with pump power ~ 430 µW. The photon-pair production rate at this optimum CAR value is about 0.02 (77K) per pulse. It is noticed that the CAR value of 130 at 77K is significantly higher by factor of 4-5 than the CAR value of 29 at 300K.

We then created the polarization entangled state $|H_iH_s\rangle + |V_iV_s\rangle$ using the HNLF in the counter propagating scheme (CPS). The fidelity of the two-photon polarization-entangled state is examined by measuring the two-photon interference fringe of the signal and idler photons. For this experiment, the polarization angles of signal and idler photons are denoted as θ_1 and θ_2. We set $\theta_1 = 0°$ and $\theta_1 = 135°$ at signal channel and vary θ_2 at idler channel, then record the coincidence counts for about 68 s. Two-photon interference (TPI) measurement with HNLF at 77K is shown in Fig. 5. The visibility of two-photon interference (TPI) > 98% is obtained when HNLF is cooled to 77K.
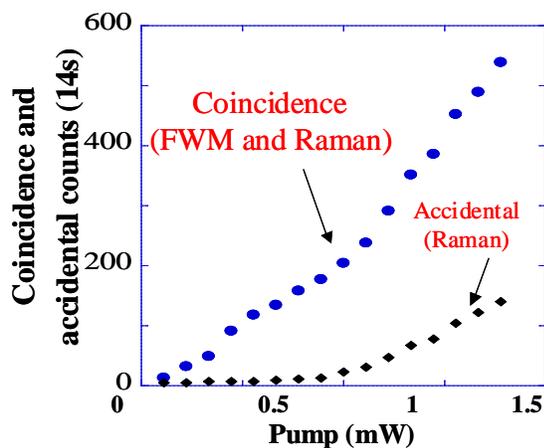

Fig.3. Coincidence (Blue square) and accidental (Black triangle) counts versus pump power for 77K.
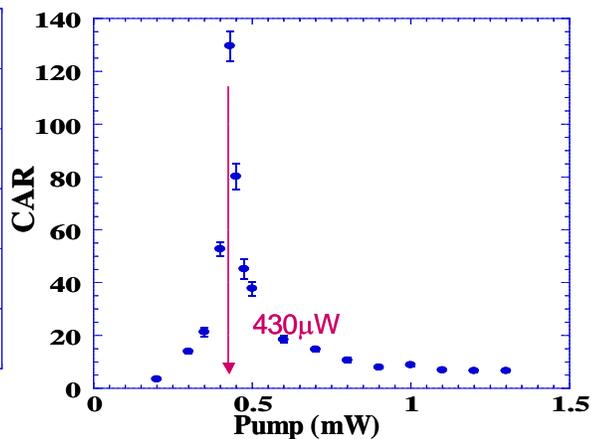
Fig.4. Coincidence to accidental coincidence ratio (CAR) versus pump power with HNLF at 77K .

We also perform the Bell's inequality violation test for verifying the non-locality behavior of the polarization-entangled photon pair generated with the HNLF. Coincidence counts of 16 different combination analyzer settings with θ_1 = 0°, 90°, -45°, 45°, and θ_2 = -22.5°, 67.5°, 22.5°, 112.5° are recorded for Bell state $\mid H_i\,V_s\,\rangle - \mid V_i\,H_s\,\rangle$. We measure the **|S|** parameters using the Clauser, Horne, Shimony, and Holt form of Bell's inequality [18], which comply with $|S| \leq 2$ for any local realistic system. The measurement of Bell's inequality violation for HNLF at 300K and 77K are shown in Table 2. At 300K we obtained |S| = 2.267 ± 0.054 , which violates Bell's inequality by almost five standard deviations. When the HNLF is cooled to 77 K, |S| = 2.788 ± 0.064, the violation of Bell's inequality by more than 12 standard deviations is observed.

All these measurements are obtained without subtracting the accidental coincidence counts that are due to Raman, or any background noise photons, and only detector dark counts are subtracted.

| Violation of Bell's inequality $|S| \leq 2$, for the state $|H_i\,V_s\rangle$ - $|V_i\,H_s\rangle$		
Temperature	|S|	Violation
300 K	2.267 ± 0.054	4.95 σ
77 K	2.788 ± 0.064	12.31σ
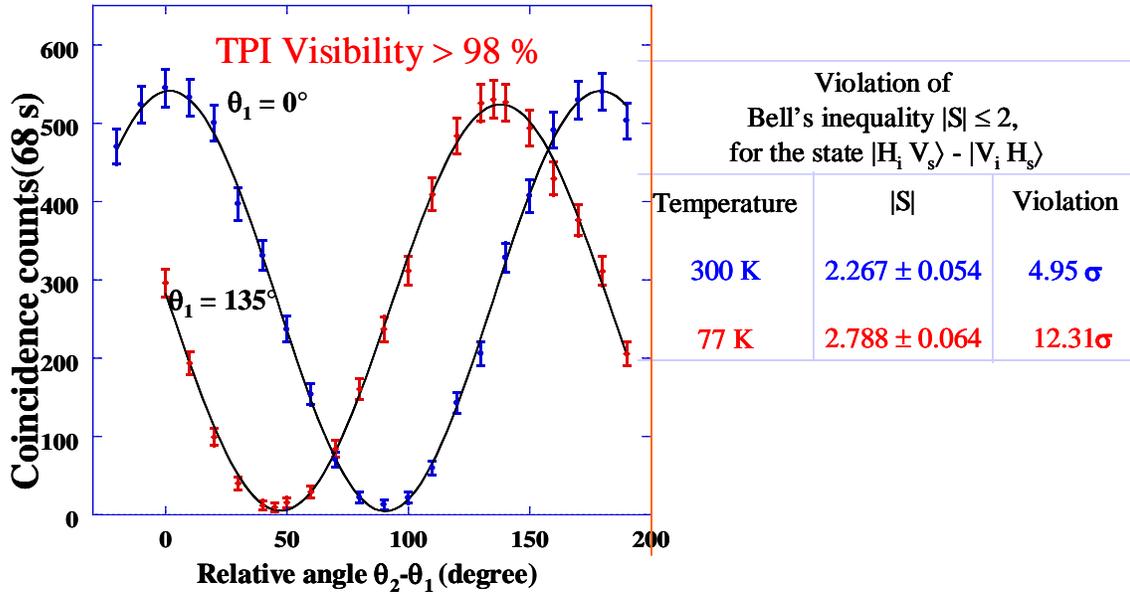
Fig.5. (Left) Two-photon interference fringes with HNLF at 77K (a) θ_1 = 0° and (b) θ_1 = 135°. (Right). The violation of Bell's inequality for the state of $|H_i\,V_s\rangle - |V_i\,H_s\rangle$.

4.3 Correlated/Entangled Photon-Pair through a Random Media

The polarization-correlated and polarization-entangled photon-pairs at telecom wavelengths are created via a spontaneous four-wave mixing process by adopting a compact counter propagating scheme (CPS) with a 10 m length of highly nonlinear fiber (HNLF). The photon-pair emerges from the CPS separated by DWDM filters with 1 nm bandwidth at 1560.6 nm and 1547.7 nm, suppressing the pump pulse at 1554.1 nm with isolation of greater than 110 dB. The output photons from the signal channel are guided through the polarization analyzer consisting of a quarter-wave plate (QWP), a half-wave plate (HWP) and a polarizing beam splitter (PBS). On the other hand, the collimated idler photons in single spatial mode are guided through a similar setup with an additional multiple scattering random medium inserted before the PBS as shown in Fig.6. The scattered photons emerge from the random medium are collected by using fiber-to-free space coupler (NA=0.25), which is placed closely right after the PBS.
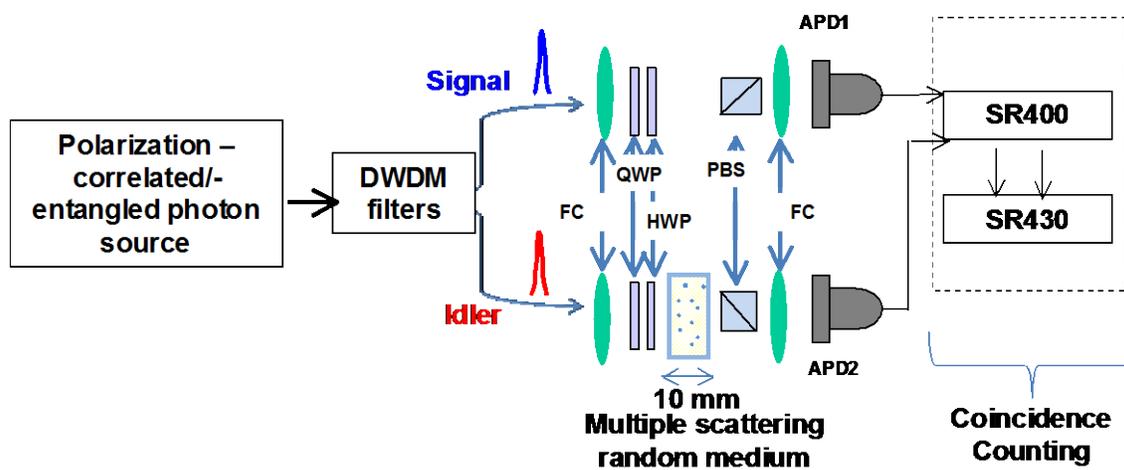
Fig. 6. Experiment setup for measuring CAR and two-photon interference of the signal photon in a normal channel and the idler photon experiencing multiple scattering events.

The multiple scattering random media is prepared by dispersing uniform polystyrene microspheres (Duke Standards) in oil suspension, and kept in a quartz cuvette with 10 mm width.

Considering the effect of the standard loss (optical attenuator) on the quantum correlation of the photon-pair, we confirm that the attenuation (~3 dB) of ballistic photons is similar for all scattering samples. We measure (i) the coincidence count to accidental-coincidence count ratio (CAR) of polarization-correlated photon-pairs and (ii) two-photon-

interference (TPI) of polarization-entangled photon-pairs to characterize effect of multiple scattering on quantum correlation of photon-pairs.

The visibility V_{cor} of a polarization-correlated photon-pair is calculated from the coincidence count (CC) and accidental-coincidence count (AC), where $V_{cor} = \dfrac{Cc - Ac}{Cc + Ac}$.
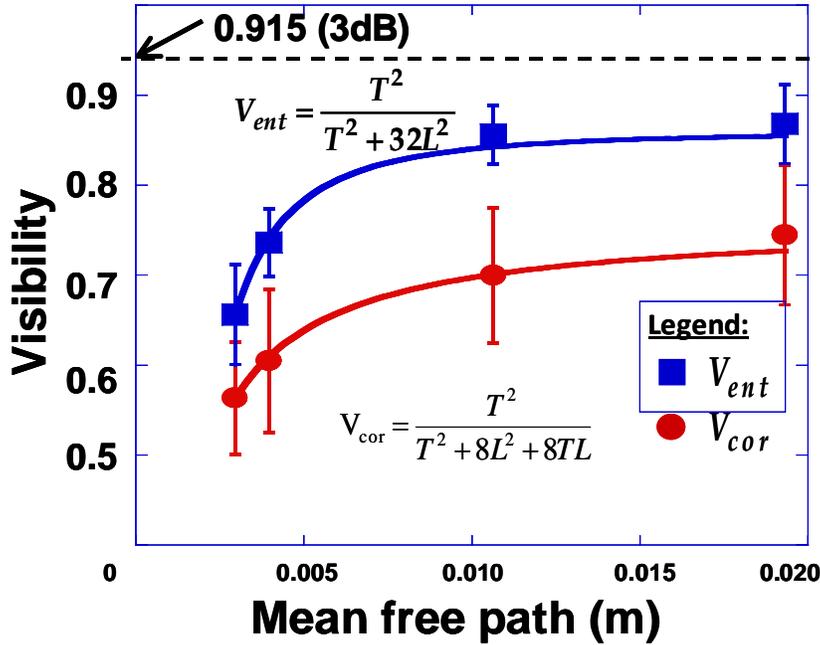

Fig.7. The V_{ent} (Blue square) and V_{cor} (Red dot) versus scattering mean free path, the solid lines are fitting curves for V_{ent} and V_{cor}. The dashed line is the visibility measured with 3 dB standard loss.

The visibility V_{ent} of polarization-entangled photon-pairs is measured directly from two photon interference. All these measurements are made with the HNLF at room temperature (300K).

We measure the V_{cor} and V_{ent} with the idler photon propagating through the random media with different scattering mean free paths as depicted in Fig.7. For comparison, we also measure the V_{cor} and V_{ent} with a standard loss (optical attenuator) of 3 dB at idler channel and obtain value of 91.5% as indicated with the dashed line in Fig.7. One can see that V_{cor} and V_{ent} obtained from the multiple scattering random media are lower compared to the case of standard loss. Also, it is noticed that V_{cor} and V_{ent} obtained from the multiple scattering random media are proportional to scattering mean free path as shown in Fig.7. All the measurements with random media are made with ~ 3 dB loss (0.7 dB of oil absorption and 2.3 dB loss due to coupling

efficiency). Therefore, the deterioration in visibility is due to depolarization of the idler photon in the multiple scattering random medium. As the idler photon scattered through the random medium, its polarization direction and phase change randomly as a result of different scattering paths in random the multiple scattering process. Remarkably, we observe that V_{ent} is significantly higher than V_{cor} for all random media with different scattering mean free paths. This observation attests that quantum correlation of polarization-entangled photon-pairs is better preserved as it propagates through the multiple scattering medium.

We demonstrate that multiple scattering in a transmission channel is detrimental to the quantum correlation of both polarization-correlated and polarization-entangled photon-pairs. In addition, we observe that polarization entanglement of photon-pairs is better preserved as it propagates through multiple scattering random medium; hence will be a superior candidate for free space long distance quantum key distribution compared to correlated photon-pairs.

4.4 Raman Photon in Fiber Source enhance Depolarization Effect.

CAR at 500 µW

"1" = Raman noise photons

"x" = Depolarization noise photons

	3dB	Turbid medium
300K	14.1	12.8
77K	56.5	48.4

$$\frac{14.1}{1+x} = 12.8 \qquad x = \frac{1.3}{12.8} = 0.1$$

$$\frac{14.1}{\frac{1}{4}+x'} = 48.4 \qquad x' = \frac{0.1}{2.4} = 0.04$$

($l = 0.019\text{m}, \phi = 0.5\mu\text{m}$)
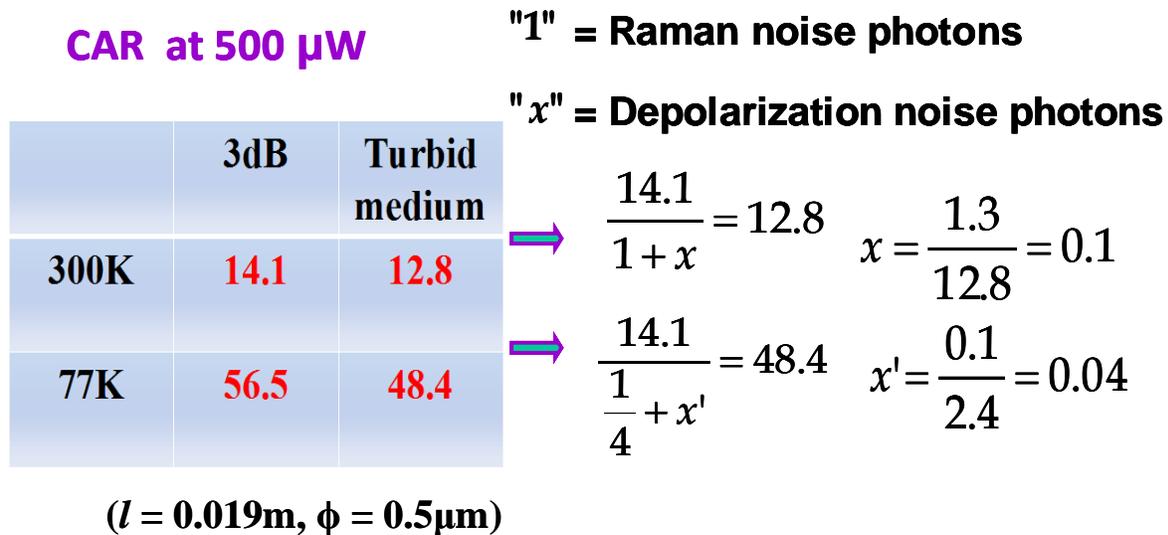
Table 2. Showing the Raman photon increases the depolarization effect in the medium by using the CAR measurement.

To identify and separate Raman photons from the noise photons induced by the depolarization of idler photon, we suppress the Raman noise photons by cooling the HNLF to 77K. We compare the CAR for the standard loss of 3 dB and scattering medium with HNLF at 300K and 77K with same average pump power. As shown in Table 3, for the standard loss of 3 dB, the CAR3dB loss is 14.1 (300K) and 56.5 (77K). For scattering random medium, the CARRM is

12.8 (300K) and 48.4 (77K). From the results with the fiber at 300K, we solve $\dfrac{14.1}{1+x} = 12.8$,

where "1" is due to the Raman photons. We obtain $x = \dfrac{1.3}{12.8} = 0.1$, which means these depolarization noise photons are about ten times smaller than Raman photons. As the fiber cooled to 77K, Raman photon is suppressed by a factor of 4 [13]. We found that $\dfrac{14.1}{1/4 + x'} = 48$, where we can obtain $x' = \dfrac{0.1}{2.4}$ indicating the suppression in depolarization noise photon. This observation shows that the presence of Raman noise photons increase depolarization effects in multiple scattering processes.

5 FINAL CONCLUSION

We have demonstrated the generation of telecom band polarization-entangled photon pair in a 10 m length of HNLF (γ = 30 W/km) via spontaneous SFWM using a compact CPS. The HNLF based polarization-entangled photon pair exhibits high visibility of TPI (>98%) and the violation of Bell's inequality >12 standard deviations with the fiber at 77K. A compact cooling system can be developed for a short HNLF length in the future.

We have demonstrated that both standard loss and multiple scattering in a transmission channel are detrimental to the quantum correlation and interference of both polarization-correlated and polarization-entangled photon-pairs. We found that polarization-entangled photon-pairs are better preserved than polarization-correlated photon-pairs in multiple scattering processes. In addition, we observe that Raman noise photons can increase depolarization effects and degrade the purity of the photon-pairs in multiple scattering processes.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

H   : horizontal Polarization.

V   : vertical Polarization.

i   : idler for one of the photon-pair generated in four-wave mixing process.

s   : signal for one of the photon-pair generated in four-wave mixing process.

χ : the Kerr nonlinearity.

k   : wave vector.

DSF   : dispersion shifted fiber.

K   : Kelvin.

γ : coupling coefficient.

HNLF   : highly nonlinear fiber.

CAR   : coincidence to accidental ratio.

CPS   : counter propagating scheme.

PCF   : photonic crystal fiber.

TPI   : two-photon interference.

k_B : Boltzmann's constant.

h :Planck's constant.

LN_2 : liquid nitrogen.

σ : Standard deviation.

AC   : accidental count.

CC   : coincidence count.